

1 Static Semantics

$\boxed{\Theta; \Delta; \Gamma \vdash e : t}$ Typing rules for expressions

$$\frac{}{\Theta; \Delta; \cdot, x : t \vdash x : t} \text{TY_VAR_LIN}$$

$$\frac{x : t \in \Delta}{\Theta; \Delta; \cdot \vdash x : t} \text{TY_VAR}$$

$$\frac{\begin{array}{l} \Theta; \Delta; \Gamma \vdash e : t \\ \Theta; \Delta; \Gamma', x : t \vdash e' : t' \end{array}}{\Theta; \Delta; \Gamma, \Gamma' \vdash \mathbf{let } x = e \mathbf{ in } e' : t'} \text{TY_LET}$$

$$\frac{}{\Theta; \Delta; \cdot \vdash () : \mathbf{unit}} \text{TY_UNIT_INTRO}$$

$$\frac{\begin{array}{l} \Theta; \Delta; \Gamma \vdash e : \mathbf{unit} \\ \Theta; \Delta; \Gamma' \vdash e' : t \end{array}}{\Theta; \Delta; \Gamma, \Gamma' \vdash \mathbf{let } () = e \mathbf{ in } e' : t} \text{TY_UNIT_ELIM}$$

$$\frac{}{\Theta; \Delta; \cdot \vdash \mathbf{true} : \mathbf{bool}} \text{TY_BOOL_TRUE}$$

$$\frac{}{\Theta; \Delta; \cdot \vdash \mathbf{false} : \mathbf{bool}} \text{TY_BOOL_FALSE}$$

$$\frac{\begin{array}{l} \Theta; \Delta; \Gamma \vdash e : \mathbf{!bool} \\ \Theta; \Delta; \Gamma' \vdash e_1 : t' \\ \Theta; \Delta; \Gamma' \vdash e_2 : t' \end{array}}{\Theta; \Delta; \Gamma, \Gamma' \vdash \mathbf{if } e \mathbf{ then } e_1 \mathbf{ else } e_2 : t} \text{TY_BOOL_ELIM}$$

$$\frac{}{\Theta; \Delta; \cdot \vdash k : \mathbf{int}} \text{TY_INT_INTRO}$$

$$\frac{}{\Theta; \Delta; \cdot \vdash el : \mathbf{elt}} \text{TY_ELT_INTRO}$$

$$\frac{\begin{array}{l} \Theta; \Delta; \cdot \vdash v : t \\ v \neq l \end{array}}{\Theta; \Delta; \cdot \vdash \mathbf{Many } v : \mathbf{!}t} \text{TY_BANG_INTRO}$$

$$\frac{\begin{array}{l} \Theta; \Delta; \Gamma \vdash e : \mathbf{!}t \\ \Theta; \Delta, x : t; \Gamma' \vdash e' : t' \end{array}}{\Theta; \Delta; \Gamma, \Gamma' \vdash \mathbf{let Many } x = e \mathbf{ in } e' : t'} \text{TY_BANG_ELIM}$$

$$\frac{\begin{array}{l} \Theta; \Delta; \Gamma \vdash e : t \\ \Theta; \Delta; \Gamma' \vdash e' : t' \end{array}}{\Theta; \Delta; \Gamma, \Gamma' \vdash (e, e') : t \otimes t'} \text{TY_PAIR_INTRO}$$

$$\frac{\begin{array}{l} \Theta; \Delta; \Gamma \vdash e_{12} : t_1 \otimes t_2 \\ \Theta; \Delta; \Gamma', a : t_1, b : t_2 \vdash e : t \end{array}}{\Theta; \Delta; \Gamma, \Gamma' \vdash \mathbf{let } (a, b) = e_{12} \mathbf{ in } e : t} \text{TY_PAIR_ELIM}$$

$$\begin{array}{c}
\frac{\Theta \vdash t' \text{ Type} \quad \Theta; \Delta; \Gamma, x : t' \vdash e : t}{\Theta; \Delta; \Gamma \vdash \mathbf{fun} \, x : t' \rightarrow e : t' \multimap t} \quad \text{TY_LAMBDA} \\
\\
\frac{\Theta; \Delta; \Gamma \vdash e : t' \multimap t \quad \Theta; \Delta; \Gamma' \vdash e' : t'}{\Theta; \Delta; \Gamma, \Gamma' \vdash e \, e' : t} \quad \text{TY_APP} \\
\\
\frac{\Theta, fc; \Delta; \Gamma \vdash e : t}{\Theta; \Delta; \Gamma \vdash \mathbf{fun} \, fc \rightarrow e : \forall fc. t} \quad \text{TY_GEN} \\
\\
\frac{\Theta \vdash f \text{ Perm} \quad \Theta; \Delta; \Gamma \vdash e : \forall fc. t}{\Theta; \Delta; \Gamma \vdash e[f] : t[f/fc]} \quad \text{TY_SPC} \\
\\
\frac{\Theta; \Delta, g : t \multimap t'; \cdot, x : t \vdash e : t'}{\Theta; \Delta; \cdot \vdash \mathbf{fix} \, (g, x : t, e : t') : t \multimap t'} \quad \text{TY_FIX}
\end{array}$$

2 Dynamic Semantics

$$\boxed{\langle \sigma, e \rangle \rightarrow \text{Config}} \quad \text{Operational semantics}$$

$$\frac{}{\langle \sigma, \mathbf{let} \, () = () \mathbf{in} \, e \rangle \rightarrow \langle \sigma, e \rangle} \quad \text{OP_LET_UNIT}$$

$$\frac{}{\langle \sigma, \mathbf{let} \, x = v \mathbf{in} \, e \rangle \rightarrow \langle \sigma, e[x/v] \rangle} \quad \text{OP_LET_VAR}$$

$$\frac{}{\langle \sigma, \mathbf{if} \, (\mathbf{Many} \, \mathbf{true}) \mathbf{then} \, e_1 \mathbf{else} \, e_2 \rangle \rightarrow \langle \sigma, e_1 \rangle} \quad \text{OP_IF_TRUE}$$

$$\frac{}{\langle \sigma, \mathbf{if} \, (\mathbf{Many} \, \mathbf{false}) \mathbf{then} \, e_1 \mathbf{else} \, e_2 \rangle \rightarrow \langle \sigma, e_2 \rangle} \quad \text{OP_IF_FALSE}$$

$$\frac{}{\langle \sigma, \mathbf{let} \, \mathbf{Many} \, x = \mathbf{Many} \, v \mathbf{in} \, e \rangle \rightarrow \langle \sigma, e[x/v] \rangle} \quad \text{OP_LET_MANY}$$

$$\frac{}{\langle \sigma, \mathbf{let} \, (a, b) = (v_1, v_2) \mathbf{in} \, e \rangle \rightarrow \langle \sigma, e[a/v_1][b/v_2] \rangle} \quad \text{OP_LET_PAIR}$$

$$\frac{}{\langle \sigma, (\mathbf{fun} \, fc \rightarrow v)[f] \rangle \rightarrow \langle \sigma[f c/f], v[f c/f] \rangle} \quad \text{OP_FRAC_PERM}$$

$$\frac{}{\langle \sigma, \mathbf{fix} \, (g, x : t, e : t') \, v \rangle \rightarrow \langle \sigma, e[x/v][g/\mathbf{fix} \, (g, x : t, e : t')] \rangle} \quad \text{OP_APP_FIX}$$

$$\frac{}{\langle \sigma, (\mathbf{fun} \, x : t \rightarrow e) \, v \rangle \rightarrow \langle \sigma, e[x/v] \rangle} \quad \text{OP_APP_LAMBDA}$$

$$\frac{\langle \sigma, e \rangle \rightarrow \langle \sigma', e' \rangle}{\langle \sigma, C[e] \rangle \rightarrow \langle \sigma', C[e'] \rangle} \quad \text{OP_CONTEXT}$$

$$\frac{\langle \sigma, e \rangle \rightarrow \mathbf{err}}{\langle \sigma, C[e] \rangle \rightarrow \mathbf{err}} \quad \text{OP_CONTEXT_ERR}$$

$$\frac{0 \leq k_1, k_2 \quad l \text{ fresh}}{\langle \sigma, \mathbf{matrix} \ k_1 \ k_2 \rangle \rightarrow \langle \sigma + \{l \mapsto_1 M_{k_1, k_2}\}, l \rangle} \quad \text{OP_MATRIX}$$

$$\frac{k_1 < 0 \text{ or } k_2 < 0}{\langle \sigma, \mathbf{matrix} \ k_1 \ k_2 \rangle \rightarrow \mathbf{err}} \quad \text{OP_MATRIX_NEG}$$

$$\frac{}{\langle \sigma + \{l \mapsto_1 m_{k_1, k_2}\}, \mathbf{free} \ l \rangle \rightarrow \langle \sigma, () \rangle} \quad \text{OP_FREE}$$

$$\frac{}{\langle \sigma + \{l \mapsto_f m_{k_1, k_2}\}, \mathbf{share}[f] \ l \rangle \rightarrow \langle \sigma + \{l \mapsto_{\frac{1}{2}f} m_{k_1, k_2}\} + \{l \mapsto_{\frac{1}{2}f} m_{k_1, k_2}\}, (l, l) \rangle} \quad \text{OP_SHARE}$$

$$\frac{}{\langle \sigma + \{l \mapsto_{\frac{1}{2}f} m_{k_1, k_2}\} + \{l \mapsto_{\frac{1}{2}f} m_{k_1, k_2}\}, \mathbf{unshare}[f] \ l \ l \rangle \rightarrow \langle \sigma + \{l \mapsto_f m_{k_1, k_2}\}, l \rangle} \quad \text{OP_UNSHARE_EQ}$$

$$\frac{l \neq l'}{\langle \sigma + \{l \mapsto_{\frac{1}{2}f} m_{k_1, k_2}\} + \{l' \mapsto_{\frac{1}{2}f} m'_{k_1, k_2}\}, \mathbf{unshare}[f] \ l \ l' \rangle \rightarrow \mathbf{err}} \quad \text{OP_UNSHARE_NEQ}$$

$$\frac{\begin{aligned} \sigma' &\equiv \sigma + \{l_1 \mapsto_{fc_1} m_{1k_1, k_2}\} + \{l_2 \mapsto_{fc_2} m_{2k_2, k_3}\} \\ \sigma_1 &\equiv \sigma' + \{l_3 \mapsto_1 m_{3k_1, k_3}\} \\ \sigma_2 &\equiv \sigma' + \{l_3 \mapsto_1 (m_1 m_2 + m_3)_{k_1, k_3}\} \end{aligned}}{\langle \sigma_1, \mathbf{gemm}[fc_1] \ l_1 [fc_2] \ l_2 \ l_3 \rangle \rightarrow \langle \sigma_2, ((l_1, l_2), l_3) \rangle} \quad \text{OP_GEMM_MATCH}$$

$$\frac{\begin{aligned} k_2 \neq k'_2 \\ \sigma' &\equiv \sigma + \{l_1 \mapsto_{fc_1} m_{1k_1, k_2}\} + \{l_2 \mapsto_{fc_2} m_{2k'_2, k_3}\} \end{aligned}}{\langle \sigma' + \{l_3 \mapsto_1 m_{1k_1, k_3}\}, \mathbf{gemm}[fc_1] \ l_1 [fc_2] \ l_2 \ l_3 \rangle \rightarrow \mathbf{err}} \quad \text{OP_GEMM_MISMATCH}$$

3 Interpretation

3.1 Definitions

Operationally, $\text{Heap} \sqsubseteq \text{Loc} \times \text{Permission} \times \text{Matrix}$ (a multiset), denoted with a σ .

Define its *interpretation* to be $\text{Loc} \rightarrow \text{Permission} \times \text{Matrix}$ with $\star : \text{Heap} \times \text{Heap} \rightarrow \text{Heap}$ as follows:

$$(\varsigma_1 \star \varsigma_2)(l) \equiv \begin{cases} \varsigma_1(l) & \text{if } l \in \text{dom}(\varsigma_1) \wedge l \notin \text{dom}(\varsigma_2) \\ \varsigma_2(l) & \text{if } l \in \text{dom}(\varsigma_2) \wedge l \notin \text{dom}(\varsigma_1) \\ (f_1 + f_2, m) & \text{if } (f_1, m) = \varsigma_1(l) \wedge (f_2, m) = \varsigma_2(l) \wedge f_1 + f_2 \leq 1 \\ \text{undefined} & \text{otherwise} \end{cases}$$

Commutativity and associativity of \star follows from that of $+$.

$\varsigma_1 \star \varsigma_2$ is *defined* if it is for all $l \in \text{dom}(\varsigma_1) \cup \text{dom}(\varsigma_2)$.

Define $\mathcal{H}[\![\sigma]\!] = \star_{(l, f, m) \in \sigma} [l \mapsto_f m]$ and **implicitly denote** $\varsigma \equiv \mathcal{H}[\![\theta(\sigma)]\!]$.

The n -fold iteration for the \rightarrow (functional) relation, is also a (functional) relation:

$$\forall n. \mathbf{err} \rightarrow^n \mathbf{err} \quad \langle \sigma, v \rangle \rightarrow^n \langle \sigma, v \rangle \quad \langle \sigma, e \rangle \rightarrow^0 \langle \sigma, e \rangle \quad \langle \sigma, e \rangle \rightarrow^{n+1} ((\langle \sigma, e \rangle \rightarrow) \rightarrow^n)$$

Hence, all bounded iterations end in either an **err**, a heap-and-expression or a heap-and-value.

3.2 Interpretation

$$\mathcal{V}_k[\mathbf{unit}] = \{(\emptyset, *)\}$$

$$\mathcal{V}_k[\mathbf{bool}] = \{(\emptyset, true), (\emptyset, false)\}$$

$$\mathcal{V}_k[\mathbf{int}] = \{(\emptyset, n) \mid 2^{-63} \leq n \leq 2^{63} - 1\}$$

$$\mathcal{V}_k[\mathbf{elt}] = \{(\emptyset, f) \mid f \text{ a IEEE Float64 } \}$$

$$\mathcal{V}_k[f \mathbf{mat}] = \{(\{l \mapsto_{2^{-f}} -\}, l)\}$$

$$\mathcal{V}_k[!t] = \{(\emptyset, \mathbf{Many} \ v) \mid (\emptyset, v) \in \mathcal{V}_k[t]\}$$

$$\mathcal{V}_k[\forall fc. t] = \{(\varsigma, \mathbf{fun} \ fc \rightarrow v) \mid \forall f. (\varsigma[fc/f], v[fc/f]) \in \mathcal{V}_{k-1}[t[fc/f]]\}$$

$$\mathcal{V}_k[t_1 \otimes t_2] = \{(\varsigma_1 \star \varsigma_2, (v_1, v_2)) \mid (\varsigma_1, v_1) \in \mathcal{V}_k[t_1] \wedge (\varsigma_2, v_2) \in \mathcal{V}_k[t_2]\}$$

$$\begin{aligned} \mathcal{V}_k[t' \multimap t] = \{(\varsigma_v, v) \mid (v \equiv \mathbf{fun} \ x : t' \rightarrow e \vee v \equiv \mathbf{fix}(g, x : t', e : t)) \wedge \\ \forall j \leq k, (\varsigma_{v'}, v') \in \mathcal{V}_j[t']. \varsigma_v \star \varsigma_{v'} \text{ defined} \Rightarrow (\varsigma_v \star \varsigma_{v'}, v \ v') \in \mathcal{C}_j[t]\} \end{aligned}$$

$$\begin{aligned} \mathcal{C}_k[t] = \{(\varsigma_s, e_s) \mid \forall j < k, \sigma_r. \varsigma_s \star \varsigma_r \text{ defined} \Rightarrow \langle \sigma_s + \sigma_r, e_s \rangle \rightarrow^j \mathbf{err} \vee \exists \sigma_f, e_f. \\ \langle \sigma_s + \sigma_r, e_s \rangle \rightarrow^j \langle \sigma_f + \sigma_r, e_f \rangle \wedge (e_f \text{ is a value} \Rightarrow (\varsigma_f \star \varsigma_r, e_f) \in \mathcal{V}_{k-j}[t])\} \end{aligned}$$

$$\mathcal{I}_k[\cdot]\theta = \{\emptyset\}$$

$$\mathcal{I}_k[\Delta, x : t]\theta = \{\delta[x \mapsto v_x] \mid \delta \in \mathcal{I}_k[\Delta]\theta \wedge (\emptyset, v_x) \in \mathcal{V}_k[\theta(t)]\}$$

$$\mathcal{L}_k[\cdot]\theta = \{(\emptyset, [])\}$$

$$\mathcal{L}_k[\Gamma, x : t]\theta = \{(\varsigma \star \varsigma_x, \gamma[x \mapsto v_x]) \mid (\varsigma, \gamma) \in \mathcal{L}_k[\Gamma]\theta \wedge (\varsigma_x, v_x) \in \mathcal{V}_k[\theta(t)]\}$$

$$\begin{aligned} \mathcal{H}[\sigma] &= \star_{(l, f, m) \in \sigma} [l \mapsto_f m] \\ \varsigma &\equiv \mathcal{H}[\theta(\sigma)] \end{aligned}$$

$$\begin{aligned} {}_k[\Theta; \Delta; \Gamma \vdash e : t] &= \forall \theta, \delta, \gamma, \sigma. \Theta = \text{dom}(\theta) \wedge (\varsigma, \gamma) \in \mathcal{L}_k[\Gamma]\theta \wedge \delta \in \mathcal{I}_k[\Delta]\theta \Rightarrow \\ &\quad (\varsigma, \theta(\delta(\gamma(e)))) \in \mathcal{C}_k[\theta(t)] \end{aligned}$$

4 Lemmas

4.1 $\forall \sigma_s, \sigma_r, e. \zeta_s \star \zeta_r \text{ defined} \Rightarrow \forall n. \langle \sigma_s, e \rangle \rightarrow^n = \langle \sigma_s + \sigma_r, e \rangle \rightarrow^n$

SUFFICES: By induction on n , consider only the cases $\langle \sigma_s, e \rangle \rightarrow \langle \sigma_f, e_f \rangle$ where $\sigma_s \neq \sigma_f$.

PROOF SKETCH: Only $\text{OP_}\{\text{FREE, MATRIX, SHARE, UNSHARE_EQ, GEMM_MATCH}\}$ change the heap: the rest are either parametric in the heap or step to an **err**.

PROVE: $\langle \sigma_s + \sigma_r, e \rangle \rightarrow \langle \sigma_f + \sigma_r, e_f \rangle$.

$\langle 1 \rangle 1$. CASE: OP_FREE , $\sigma_s \equiv \sigma' + \{l \mapsto_1 m\}$, $\sigma_f = \sigma'$.

PROOF: Instantiate OP_FREE with $(\sigma' + \sigma_r) + \{l \mapsto_1 m\}$,
valid because $l \notin \text{dom}(\zeta_r)$ by $\zeta' \star [l \mapsto_1 m] \star \zeta_r$ defined (assumption).

$\langle 1 \rangle 2$. CASE: OP_MATRIX

PROOF: Rule has no requirements on σ_s so will also work with $\sigma_s + \sigma_r$.

$\langle 1 \rangle 3$. CASE: OP_SHARE , $\sigma_s \equiv \sigma' + \{l \mapsto_f m\}$, $\sigma_f = \sigma' + \{l \mapsto_{\frac{1}{2}.f} m\} + \{l \mapsto_{\frac{1}{2}.f} m\}$.

PROOF: Union-ing σ_r does not remove $l \mapsto_f m$, so that can be split out of $\sigma_s + \sigma_r$ as before.

$\langle 1 \rangle 4$. CASE: OP_UNSHARE_EQ , $\sigma_s \equiv \sigma' + \{l \mapsto_{\frac{1}{2}.f} m\} + \{l \mapsto_{\frac{1}{2}.f} m\}$, $\sigma_f = \sigma' + \{l \mapsto_f m\}$.

$\langle 2 \rangle 1$. Union-ing σ_r does not remove $l \mapsto_{\frac{1}{2}.f} m$, so that can still be split out of $\sigma_s + \sigma_r$.

$\langle 2 \rangle 2$. There may also be other valid splits introduced by σ_r .

$\langle 2 \rangle 3$. However, by assumption of $\zeta_s \star \zeta_r$ defined, any splitting of $\sigma_s + \sigma_r$ will satisfy $f \leq 1$.

$\langle 1 \rangle 5$. CASE: OP_GEMM_MATCH

$\langle 2 \rangle 1$. By assumption of $\zeta_s \star \zeta_r$ defined, either l_1 (or l_2 , or both) are not in σ_r , or they are and the matrix values they point to are the same.

$\langle 2 \rangle 2$. The permissions (of l_1 and/or l_2) may differ, but OP_GEMM_MATCH universally quantifies over them and leaves them unchanged, so they are irrelevant.

$\langle 2 \rangle 3$. Only the pointed to matrix value at l_3 changes.

$\langle 2 \rangle 4$. SUFFICES: $l_3 \notin \pi_1[\sigma_r]$.

$\langle 2 \rangle 5$. By assumption of $\zeta_s \star \zeta_r$ defined, $l_3 \notin \text{dom}(\zeta_r)$.

$\langle 2 \rangle 6$. Hence $l_3 \notin \pi_1[\sigma_r]$.

4.2 $\forall k, t. \mathcal{V}_k[t] \subseteq \mathcal{C}_k[t]$

Follows from definition of $\mathcal{C}_k[t]$, \rightarrow^j ($\forall n. \langle \sigma, v \rangle \rightarrow^n \langle \sigma, v \rangle$) for arbitrary $j \leq k$ and 4.1.

4.3 $\forall \theta, \delta, \gamma, v. \theta(\delta(\gamma(v)))$ is a value.

θ is irrelevant because it only maps fractional permission variables to fractional permissions. By construction, δ and γ only map variables to values, and values are closed under substitution.

4.4 $\forall k, \sigma, \sigma', e, e', t. (\varsigma', e') \in \mathcal{C}_k[t] \wedge \langle \sigma, e \rangle \rightarrow \langle \sigma', e' \rangle \Rightarrow (\varsigma, e) \in \mathcal{C}_{k+1}[t]$

In the lemma, and for the rest of its proof, $\varsigma = \mathcal{H}[\sigma]$.

ASSUME: arbitrary $j < k + 1$, and σ_r such that $\varsigma \star \sigma_r$ defined.

$\langle 1 \rangle 1$. CASE: $j = 0$. Clearly $\sigma_f = \sigma_s + \sigma_r$ and $e' = e$.

Remains to show that if e is a value then $(\varsigma_s \star \sigma_r, e) \in \mathcal{V}_k[t]$.

This is true vacuously, because by assumption, e is not a value.

$\langle 1 \rangle 2$. CASE: $j \geq 1$. We have $\langle \sigma, e \rangle \rightarrow^j = \langle \sigma', e' \rangle \rightarrow^{j-1}$.

Instantiate $(\varsigma', e') \in \mathcal{C}_k[t]$, with $j - 1 < k$ and σ_r to conclude the required conditions.

4.5 $j \leq k \Rightarrow _k[\cdot] \subseteq _j[\cdot]$

For the rest of this proof, $\varsigma = \mathcal{H}[\sigma]$.

Lemma 4.4 is the inductive step for this lemma for the $\mathcal{C}[\cdot]$ case.

Need to prove for $\mathcal{V}[\cdot]$, by induction on t and then index.

SUFFICES: Consider only $t \multimap t'$ case, rest use k directly on structure of type.

ASSUME: Arbitrary $j \leq k$ and $(\varsigma_{v'}, v') \in \mathcal{V}_k[t \multimap t']$.

PROVE: $(\varsigma_{v'}, v') \in \mathcal{V}_j[t \multimap t']$.

$\langle 1 \rangle 1$. v' is of the correct syntactic form (lambda or fixpoint) by assumption.

$\langle 1 \rangle 2$. ASSUME: arbitrary $j' \leq j$ and $(\varsigma_v, v) \in \mathcal{V}_{j'}[t]$ such that $\varsigma_{v'} \star \varsigma_v$ is defined.

$\langle 1 \rangle 3$. SUFFICES: to show $(\varsigma_{v'} \star \varsigma_v, v'v) \in \mathcal{C}_{j'}[t']$.

$\langle 1 \rangle 4$. This is true by instantiating $(\varsigma_{v'}, v') \in \mathcal{V}_k[t \multimap t']$ with $j' \leq k$ and $(\varsigma_v, v) \in \mathcal{V}_{j'}[t]$.

4.6 $\forall \Delta, \Gamma, t, k, \theta, \delta, \gamma. \delta \in \mathcal{I}_k[\Delta]\theta \wedge \gamma \in \pi_2[\mathcal{L}_k[\Gamma]\theta] \Rightarrow \text{dom}(\Delta) = \text{dom}(\delta) \text{ and } \text{dom}(\Gamma) = \text{dom}(\gamma)$

PROOF: By induction on Δ and Γ .

4.7 $\forall k, \Gamma, \Gamma', \theta, \sigma_+, \gamma_+. (\varsigma_+, \gamma) \in \mathcal{L}_k[\Gamma, \Gamma']\theta \wedge \Gamma, \Gamma' \text{ disjoint} \Rightarrow \exists \sigma, \gamma, \sigma', \gamma'. \sigma_+ = \sigma + \sigma' \wedge \gamma, \gamma' \text{ disjoint} \wedge \gamma_+ = \gamma \cup \gamma' \wedge (\varsigma, \gamma) \in \mathcal{L}_k[\Gamma] \wedge (\varsigma', \gamma') \in \mathcal{L}_k[\Gamma']$

PROOF: By induction on Γ' .

4.8 $\forall e, \sigma, e', \sigma', \theta. \langle \sigma, e \rangle \rightarrow \langle \sigma', e' \rangle \Rightarrow \langle \theta(\sigma), \theta(e) \rangle \rightarrow \langle \theta(\sigma'), \theta(e') \rangle$

PROOF: By induction on \rightarrow .

$\langle 1 \rangle 1$. ASSUME: Arbitrary $e, \sigma, e', \sigma', \theta$ such that $\langle \sigma, e \rangle \rightarrow \langle \sigma', e' \rangle$.

$\langle 1 \rangle 2$. SUFFICES: To consider only the following rules which mention fractional permission variables.
OP_FRAC_PERM, OP_SHARE, OP_UNSHARE_(N)EQ and OP_GEMM_(MIS)MATCH.

$\langle 1 \rangle 3$. CASE: OP_FRAC_PERM.

Because substitution avoids capture,

$$\langle \theta(\sigma), \theta((\mathbf{fun} \, fc \rightarrow v) [f]) \rangle \rightarrow \langle \theta(\sigma' [fc/f]), \theta(v [fc/f]) \rangle.$$

- ⟨1⟩4. The rest of the cases are parametric in their use of fractional permission variables and so will take the same step after any substitution.
- ⟨1⟩5. COROLLARY: If $\langle \sigma [fc/f_1], e [fc/f_1] \rangle \rightarrow^n \langle \sigma_2, e'_2 \rangle$ and $\langle \sigma [fc/f_2], e [fc/f_2] \rangle \rightarrow^n \langle \sigma_2, e'_2 \rangle$, then $\exists \sigma, e'. \sigma_1 = \sigma [fc/f_1] \wedge \sigma_2 = \sigma [fc/f_2] \wedge e'_1 = e' [fc/f_1] \wedge e'_2 = e' [fc/f_2]$.

5 Soundness

$$\forall \Theta, \Delta, \Gamma, e, t. \Theta; \Delta; \Gamma \vdash e : t \Rightarrow \forall k. {}_k\llbracket \Theta; \Delta; \Gamma \vdash e : t \rrbracket$$

PROOF SKETCH: Induction over the typing judgements.

ASSUME: 1. Arbitrary $\Theta, \Delta, \Gamma, e, t$ such that $\Theta; \Delta; \Gamma \vdash e : t$.

2. Arbitrary $k, \theta, \delta, \gamma, \sigma$ such that:

a. $\Theta = \text{dom}(\theta)$

b. $\delta \in \mathcal{I}_k\llbracket \Delta \rrbracket \theta$.

c. $(\varsigma, \gamma) \in \mathcal{L}_k\llbracket \Gamma \rrbracket \theta$

3. W.l.o.g., all variables are distinct, hence Θ , $\text{dom}(\Delta)$ and $\text{dom}(\Gamma)$ are disjoint so order of θ , δ and γ (as substitutions defined recursively over expressions) is irrelevant.

PROVE: $(\varsigma, \theta(\delta(\gamma(e)))) \in \mathcal{C}_k\llbracket \theta(t) \rrbracket$.

ASSUME: Arbitrary $j < k$ and σ_r , such that $\varsigma \star \varsigma_r$ defined.

SUFFICES: $\langle \sigma + \sigma_r, e \rangle \rightarrow^j \mathbf{err} \vee \exists \sigma_f, e_f. \langle \sigma + \sigma_r, e \rangle \rightarrow^j \langle \sigma_f + \sigma_r, e_f \rangle$

$\wedge (e_f \text{ is a value} \Rightarrow (\varsigma_f \star \varsigma_r, e_f) \in \mathcal{V}_{k-j}\llbracket t \rrbracket)$.

SUFFICES: By 4.1, to show $\langle \sigma, e \rangle \rightarrow^j \mathbf{err} \vee \exists \sigma_f, e_f. \langle \sigma, e \rangle \rightarrow^j \langle \sigma_f, e_f \rangle$

$\wedge (e_f \text{ is a value} \Rightarrow (\varsigma_f, e_f) \in \mathcal{V}_{k-j}\llbracket t \rrbracket)$

$\langle 1 \rangle 1$. CASE: `TY_LET`.

$\langle 2 \rangle 1$. By induction,

1. $\forall k. {}_k\llbracket \Theta; \Delta; \Gamma \vdash e : t \rrbracket$

2. $\forall k. {}_k\llbracket \Theta; \Delta; \Gamma', x : t \vdash e' : t' \rrbracket$.

$\langle 2 \rangle 2$. By 2c, 3 and 4.7, we know there exists the following (for all k):

1. $(\varsigma_e, \gamma_e) \in \mathcal{L}_k\llbracket \Gamma \rrbracket$

2. $\gamma = \gamma_e \cup \gamma_{e'}$

3. $\sigma = \sigma_e + \sigma_{e'}$.

$\langle 2 \rangle 3$. So, using $k, \theta, \delta, \gamma_e, \sigma_e$, we have $(\varsigma_e, \theta(\delta(\gamma_e(e)))) \in \mathcal{C}_k\llbracket \theta(t) \rrbracket$.

$\langle 2 \rangle 4$. By $\langle 2 \rangle 2$ ($\gamma = \gamma_e \cup \gamma_{e'}$), have $(\varsigma_e, \theta(\delta(\gamma(e)))) \in \mathcal{C}_k\llbracket \theta(t) \rrbracket$.

$\langle 2 \rangle 5$. By definition of $\mathcal{C}_k\llbracket \cdot \rrbracket$ and $\langle 2 \rangle 2$, we instantiate with j and $\sigma_r = \sigma_{e'}$ to conclude that $\langle \theta(\sigma), \theta(\delta(\gamma(e))) \rangle$ either takes j steps to **err** or another heap-and-expression $\langle \sigma_f, e_f \rangle$.

$\langle 2 \rangle 6$. CASE: j steps to **err**

By `OP_CONTEXT_ERR`, the whole expression reduces to **err** in $j < k$ steps.

$\langle 2 \rangle 7$. CASE: j steps to another heap-and-expression.

If it is not a value, then `OP_CONTEXT` runs j times and we are done.

$\langle 2 \rangle 8$. If it is, then $\exists i \leq j. (\varsigma_f, v_1) \in \mathcal{V}_{k-i}\llbracket \theta(t_1) \rrbracket \subseteq \mathcal{V}_{k-j}\llbracket \theta(t_1) \rrbracket$ by 4.3 and 4.5.

So, `OP_CONTEXT` runs i times, and then we have the following.

SUFFICES: $(\varsigma_f \star \varsigma_{e'}, \mathbf{let } x = v \mathbf{ in } \theta(\delta(\gamma(e')))) \in \mathcal{C}_{k-i}\llbracket \theta(t') \rrbracket$ by 4.4 i times.

SUFFICES: $(\varsigma_f \star \varsigma_{e'}, \theta(\delta(\gamma(e')))[x/v]) \in \mathcal{C}_{k-i-1}\llbracket \theta(t') \rrbracket$ by 4.4.

$\langle 2 \rangle 9$. By 4.5, $(\varsigma_{e'}, \gamma_{e'}[x \mapsto v]) \in \mathcal{L}_k\llbracket \Gamma', x : t \rrbracket \theta \subseteq \mathcal{L}_{k-i-1}\llbracket \Gamma', x : t \rrbracket \theta$.

$\langle 2 \rangle 10$. Instantiate 2 of step $\langle 2 \rangle 1$ with $k - i - 1, \theta, \delta, \gamma_{e'}[x \mapsto v], \sigma_{e'}$ to conclude $(\varsigma_{e'}, \theta(\delta(\gamma_{e'}[x \mapsto v](e')))) \in \mathcal{C}_{k-i-1}\llbracket \theta(t') \rrbracket$.

- ⟨2⟩11. By 3, we have $\theta(\delta(\gamma(e')))[x/v] = \theta(\delta(\gamma_{e'}[x \mapsto v](e')))$ and by 4.1 we conclude $(\varsigma_f \star \varsigma_{e'}, \theta(\delta(\gamma(e')))[x/v]) \in \mathcal{C}_{k-i-1}[\![\theta(t')]\!]$
- ⟨1⟩2. CASE: TY_PAIR_ELIM.
PROOF SKETCH: Similar to TY_LET, but with the following key differences.
- ⟨2⟩1. When $(\varsigma_f, v) \in \mathcal{V}_{k-i}[\![\theta(t_1) \otimes \theta(t_2)]\!]$, we have $v = (v_1, v_2)$.
- ⟨2⟩2. SUFFICES: $(\varsigma_{e'}, \theta(\delta(\gamma(e')))) \in \mathcal{C}_{k-i-1}[\![\theta(t')]\!]$ by 4.4 $i + 1$ times.
- ⟨2⟩3. By 4.5, $(\varsigma_{e'}, \gamma_{e'}[a \mapsto v_1, b \mapsto v_2]) \in \mathcal{L}_k[\![\Gamma', a : t_1, b : t_2]\!]\theta \subseteq \mathcal{L}_{k-i-1}[\![\Gamma', a : t_1, b : t_2]\!]\theta$.
- ⟨2⟩4. Instantiate $_{k-i-1}[\![\Theta; \Delta; \Gamma', a : t_1, b : t_2 \vdash e' : t']\!]$ with $\theta, \delta, \gamma_{e'}[a \mapsto v_1, b \mapsto v_2], \sigma_{e'}$.
- ⟨2⟩5. By 3 (for $\gamma = \gamma_e \cup \gamma_{e'}$ and a, b), conclude $(\varsigma_{e'}, \theta(\delta(\gamma(e'[a/v_1][b/v_2]))) \in \mathcal{C}_{k-i-1}[\![\theta(t')]\!]$.
- ⟨1⟩3. CASE: TY_BANG_ELIM.
PROOF SKETCH: Similar to TY_LET, but with the following key differences.
- ⟨2⟩1. When $(\varsigma_f, v) \in \mathcal{V}_{k-i}[\![\theta(!t)]\!]$, since $\mathcal{V}_{k-i}[\![\theta(!t)]\!] = \mathcal{V}_{k-i}[\![! \theta(t)]\!]$, we have $\varsigma_f = \emptyset$ and $v = \mathbf{Many} \ v'$ for some $(\emptyset, v') \in \mathcal{V}_{k-i}[\![\theta(t)]\!]$.
- ⟨2⟩2. SUFFICES: $(\varsigma_{e'}, \mathbf{let} \ \mathbf{Many} \ x = \mathbf{Many} \ v' \ \mathbf{in} \ \theta(\delta(\gamma(e')))) \in \mathcal{C}_{k-i}[\![\theta(t)]\!]$.
- ⟨2⟩3. SUFFICES: $(\varsigma_{e'}, \theta(\delta(\gamma(e')))[x/v]) \in \mathcal{C}_{k-i-1}[\![\theta(t)]\!]$ by 4.4 $i + 1$ times.
- ⟨2⟩4. Instantiate $_{k-i-1}[\![\Theta; \Delta, x : t, \Gamma' \vdash e' : t']\!]$ with $\theta, \delta_{e'} = \delta[x \mapsto v'], \gamma_{e'}, \sigma_{e'}$.
- ⟨2⟩5. By 3, $(\varsigma_{e'}, \theta(\delta(\gamma(e')))[x/v]) \in \mathcal{C}_{k-i-1}[\![\theta(t)]\!]$.
- ⟨1⟩4. CASE: TY_UNIT_ELIM.
PROOF SKETCH: Similar to TY_LET, but with the following key differences.
- ⟨2⟩1. When $(\varsigma_f, v) \in \mathcal{V}_{k-i}[\![\mathbf{unit}]\!]$, we have $\varsigma_f = \emptyset$ and $v = ()$.
- ⟨2⟩2. SUFFICES: $(\varsigma_{e'}, \theta(\delta(\gamma(e')))) \in \mathcal{C}_{k-i-1}[\![\theta(t')]\!]$ by 4.4 $i + 1$ times.
- ⟨2⟩3. By 4.5, $(\varsigma_{e'}, \gamma_{e'}) \in \mathcal{L}_k[\![\Gamma']\!]\theta \subseteq \mathcal{L}_{k-i-1}[\![\Gamma']\!]\theta$.
- ⟨2⟩4. Instantiate $_{k-i-1}[\![\Theta; \Delta; \Gamma' \vdash e' : t']\!]$ with $\theta, \delta, \gamma_{e'}, \sigma_{e'}$.
- ⟨2⟩5. By 3 $(\varsigma_{e'}, \theta(\delta(\gamma(e')))) \in \mathcal{C}_{k-i-1}[\![\theta(t')]\!]$.
- ⟨1⟩5. CASE: TY_BOOL_ELIM.
PROOF SKETCH: Similar to TY_UNIT_ELIM but with $\text{OP_IF_}\{\text{TRUE}, \text{FALSE}\}$, $\varsigma_f = \emptyset$ and $v = \mathbf{Many} \ \text{true}$ or $v = \mathbf{Many} \ \text{false}$.
- ⟨1⟩6. CASE: TY_BANG_INTRO.
- ⟨2⟩1. We have, $e = v$ for some value $v \neq l$, $\Gamma = \emptyset$ and so $\forall k. \ _k[\![\Theta; \Delta; \cdot \vdash v : t]\!]$ by induction.
- ⟨2⟩2. SUFFICES: $(\emptyset, \mathbf{Many} \ \theta(\delta(v))) \in \mathcal{C}_k[\![! \theta(t)]\!]$ by 2c ($\varsigma = \emptyset, \gamma = []$).
- ⟨2⟩3. Instantiate $_{k-1}[\![\Theta; \Delta; \cdot \vdash v : t]\!]$ with $\theta, \delta, \gamma = [], \sigma = \emptyset$ to obtain $(\emptyset, \theta(\delta(v))) \in \mathcal{C}_k[\![\theta(t)]\!]$.
- ⟨2⟩4. Instantiate $(\emptyset, \theta(\delta(v))) \in \mathcal{C}_k[\![\theta(t)]\!]$ with $j = 0$, $\sigma_r = \emptyset$ and 4.3 ($\theta(\delta(v))$ is a value),

to conclude $(\emptyset, \theta(\delta(v))) \in \mathcal{V}_k[\![\theta(t)]\!]$.

$\langle 2 \rangle 5$. By definition of $\mathcal{V}_k[\![\theta(t)]\!]$, 4.3 and 4.2 we have $(\emptyset, \mathbf{Many} \theta(\delta(v))) \in \mathcal{C}_k[\![\theta(t)]\!]$.

$\langle 1 \rangle 7$. CASE: `TY_PAIR_INTRO`.

$\langle 2 \rangle 1$. By 2c, 3 and 4.7, we know there exists the following (for all k):

1. $(\varsigma_1, \gamma_1) \in \mathcal{L}_k[\![\Gamma_1]\!]$
2. $(\varsigma_2, \gamma_2) \in \mathcal{L}_k[\![\Gamma_2]\!]$
3. $\gamma = \gamma_1 \cup \gamma_2$
4. $\sigma = \sigma_1 + \sigma_2$.

$\langle 2 \rangle 2$. By induction,

1. $\forall k. \mathcal{L}_k[\![\Theta; \Delta; \Gamma_1 \vdash e_1 : t_1]\!]$
2. $\forall k. \mathcal{L}_k[\![\Theta; \Delta; \Gamma_2 \vdash e_2 : t_2]\!]$.

$\langle 2 \rangle 3$. Instantiate the first with $k, \theta, \delta, \gamma_1, \sigma_1$.

$\langle 2 \rangle 4$. By that and $\langle 2 \rangle 1$, $(\varsigma_1, \theta(\delta(\gamma_1(e_1)))) = (\varsigma_1, \theta(\delta(\gamma(e_1)))) \in \mathcal{C}_k[\![\theta(t)]\!]$.

$\langle 2 \rangle 5$. So, $\langle \theta(\sigma_1 + \sigma_2), \theta(\delta(\gamma_1(e_1))) \rangle$ either takes j steps to **err** or a heap-and-expression $\langle \sigma_{1f}, e_{1f} \rangle$.

$\langle 2 \rangle 6$. CASE: j steps to **err**

By `OP_CONTEXT_ERR`, the whole expression reduces to **err** in $j < k$ steps.

$\langle 2 \rangle 7$. CASE: j steps to another heap-and-expression.

If it is not a value, then `OP_CONTEXT` runs j times and we are done.

$\langle 2 \rangle 8$. If it is, then $\exists i_1 \leq j. (\varsigma_{1f}, v_1) \in \mathcal{V}_{k-i_1}[\![\theta(t_1)]\!] \subseteq \mathcal{V}_{k-j}[\![\theta(t_1)]\!]$ by 4.3 and 4.5.

So, `OP_CONTEXT` runs i_1 times, and then we have the following.

SUFFICES: By 4.4, $(\varsigma_{1f} \star \varsigma_2, (v_1, e_2)) \in \mathcal{C}_{k-i_1}[\![\theta(t_1) \otimes t_2]\!]$.

$\langle 2 \rangle 9$. Instantiate the second IH with $k, \theta, \delta, \gamma_2, \sigma_2$.

$\langle 2 \rangle 10$. So, $\langle \theta(\sigma_{1f} + \sigma_2), \theta(\delta(\gamma_2(e_2))) \rangle$ either takes j steps to **err** or a heap-and-expression $\langle \sigma_{2f}, e_{2f} \rangle$.

$\langle 2 \rangle 11$. CASE: j steps to **err**

By `OP_CONTEXT_ERR`, the whole expression reduces to **err** in $j < k$ steps.

$\langle 2 \rangle 12$. CASE: j steps to another heap-and-expression.

If it is not a value, then `OP_CONTEXT` runs j times and we are done.

$\langle 2 \rangle 13$. If it is, then $\exists i_2 \leq j. (\varsigma_{2f}, v_2) \in \mathcal{V}_{k-i_2}[\![\theta(t_2)]\!] \subseteq \mathcal{V}_{k-j}[\![\theta(t_2)]\!]$ by 4.3 and 4.5.

So, `OP_CONTEXT` runs i_2 times, and then we have the following.

SUFFICES: By 4.4, $(\varsigma_{1f} \star \varsigma_{2f}, (v_1, v_2)) \in \mathcal{V}_{k-i_1-i_2}[\![\theta(t_1) \otimes \theta(t_2)]\!]$.

$\langle 2 \rangle 14$. By 4.5 and $k - i_1 - i_2 \leq k - i_1, k - i_2$, have

- $(\varsigma_{1f}, v_1) \in \mathcal{V}_{k-i_1}[\![\theta(t_1)]\!] \subseteq \mathcal{V}_{k-i_1-i_2}[\![\theta(t_1)]\!]$ and
- $(\varsigma_{2f}, v_2) \in \mathcal{V}_{k-i_2}[\![\theta(t_2)]\!] \subseteq \mathcal{V}_{k-i_1-i_2}[\![\theta(t_2)]\!]$ as needed.

$\langle 1 \rangle 8$. CASE: `TY_LAMBDA`.

SUFFICES: By 4.2, to show $(\varsigma, \theta(\delta(\gamma(\mathbf{fun} x : t \rightarrow e)))) \in \mathcal{V}_k[\![\theta(t \multimap t')]\!]$.

ASSUME: Arbitrary $j \leq k$, $(\varsigma_v, v) \in \mathcal{V}_j[\![\theta(t)]\!]$ such that $\varsigma \star \varsigma_v$ is defined.

SUFFICES: $(\varsigma \star \varsigma_v, \theta(\delta(\gamma(\mathbf{fun} x : t \rightarrow e))) v) \in \mathcal{C}_j[\![\theta(t')]\!]$.

SUFFICES: $(\varsigma \star \varsigma_v, \theta(\delta(\gamma(e)))[x/v]) \in \mathcal{C}_{j-1}[\![\theta(t')]\!]$ by 4.4.

$\langle 2 \rangle 1$. By induction, $\forall k. {}_k\llbracket \Theta; \Delta; \Gamma, x : t \vdash e \rrbracket$.

$\langle 2 \rangle 2$. Instantiate it $j - 1, \theta, \delta, \gamma[x \mapsto v], \sigma + \sigma_v$.

$\langle 2 \rangle 3$. Hence, $(\varsigma \star \varsigma_v, \theta(\delta(\gamma[x \mapsto v](e)))) \in \mathcal{C}_{j-1}[\![\theta(t')]\!]$.

$\langle 2 \rangle 4$. By 3, $\theta(\delta(\gamma[x \mapsto v](e))) = \theta(\delta(\gamma(e)))[x/v]$, we are done.

$\langle 1 \rangle 9$. CASE: `TY_APP`.

$\langle 2 \rangle 1$. By 2c, 3 and 4.7, we know there exists the following (for all k):

1. $(\varsigma_e, \gamma_e) \in \mathcal{L}_k[\![\Gamma_e]\!]$
2. $(\varsigma_{e'}, \gamma_{e'}) \in \mathcal{L}_k[\![\Gamma_{e'}]\!]$
3. $\gamma = \gamma_e \cup \gamma_{e'}$
4. $\sigma = \sigma_e + \sigma_{e'}$.

$\langle 2 \rangle 2$. By induction,

1. $\forall k. {}_k\llbracket \Theta; \Delta; \Gamma \vdash e : t' \multimap t \rrbracket$
2. $\forall k. {}_k\llbracket \Theta; \Delta; \Gamma' \vdash e' : t' \rrbracket$.

$\langle 2 \rangle 3$. Instantiate the first with $k, \theta, \delta, \gamma_e, \sigma_e$ to conclude $(\varsigma_e, \theta(\delta(\gamma_e(e)))) \in \mathcal{C}_k[\![\theta(t') \multimap \theta(t)]\!]$.

$\langle 2 \rangle 4$. Instantiate *this* with j and $\sigma_{e'}$ and use $\langle 2 \rangle 1$ to conclude $\langle \theta(\sigma_e + \sigma_{e'}), \theta(\delta(\gamma(e))) \rangle$ either takes j steps to **err** or a heap-and-expression $\langle \sigma_f + \sigma_{e'}, e_f \rangle$.

$\langle 2 \rangle 5$. CASE: j steps to **err**

By `OP_CONTEXT_ERR`, the whole expression reduces to **err** in $j < k$ steps.

$\langle 2 \rangle 6$. CASE: j steps to another heap-and-expression.

If it is not a value, then `OP_CONTEXT` runs j times and we are done.

$\langle 2 \rangle 7$. If it is, then $\exists i_e \leq j. (\varsigma_f, e_f) \in \mathcal{V}_{k-i_e}[\![\theta(t') \multimap \theta(t)]\!] \subseteq \mathcal{V}_{k-j}[\![\dots]\!]$ by 4.3 and 4.5.

So, `OP_CONTEXT` runs i_e times, and then we have the following.

SUFFICES: By 4.4 i_e times, $(\varsigma_f \star \varsigma_{e'}, e_f e') \in \mathcal{C}_{k-i_e}[\![\theta(t')]\!]$.

$\langle 2 \rangle 8$. By 4.5, $(\varsigma_{e'}, \gamma_{e'} \in \mathcal{L}_k[\![\Gamma']\!])\theta \subseteq \mathcal{L}_{k-i_e}[\![\Gamma']\!]\theta$.

$\langle 2 \rangle 9$. So, instantiate the second IH with $k - i_e, \theta, \delta, \gamma_{e'}, \sigma_{e'}$ to conclude

$(\varsigma_{e'}, \theta(\delta(\gamma_{e'}(e')))) \in \mathcal{C}_{k-i_e}[\![\theta(t')]\!]$.

$\langle 2 \rangle 10$. Instantiate *this* with $j - i_e$ and σ_f to conclude $\langle \theta(\sigma_f + \sigma_{e'}), \theta(\delta(\gamma_{e'}(e')) \rangle$

either takes $j - i_e$ steps to **err** or $\langle \sigma_f + \sigma'_f, e'_f \rangle$.

$\langle 2 \rangle 11$. CASE: $j - i_e$ steps to **err**

By `OP_CONTEXT_ERR`, the whole expression reduces to **err** in $j - i_e < k - i_e$ steps.

$\langle 2 \rangle 12$. CASE: $j - i_e$ steps to another heap-and-expression.

If it is not a value, then `OP_CONTEXT` runs $j - i_e$ times and we are done.

$\langle 2 \rangle 13$. If it is, then $\exists i_{e'} \leq j - i_e. (\varsigma'_f, v_{e'}) \in \mathcal{V}_{k-i_e-i_{e'}}[\![\theta(t')]\!]$ by 4.3.

So, `OP_CONTEXT` runs $i_{e'}$ times, and then we have the following.

SUFFICES: By 4.4 $i_{e'}$ times, $(\varsigma_f \star \varsigma'_f, e_f e'_f) \in \mathcal{C}_{k-i_e-i_{e'}}[\![\theta(t')]\!]$.

$\langle 2 \rangle 14$. Instantiate $(\varsigma_f, e_f) \in \mathcal{V}_{k-i_e}[\![\theta(t') \multimap \theta(t)]\!]$ with $k - i_e - i_{e'} \leq k - i_e$ and

$(\varsigma_{v'}, v_{e'}) \in \mathcal{V}_{k-i_e-i_{e'}} \llbracket \theta(t') \rrbracket$, to conclude $(\varsigma_f \star \varsigma'_f, e_f e'_f) \in \mathcal{C}_{k-i_e-i_{e'}} \llbracket \theta(t) \rrbracket$ as needed.

$\langle 1 \rangle 10$. CASE: TY_GEN.

$\langle 2 \rangle 1$. By induction, $\forall k. {}_k \llbracket \Theta; fc; \Delta; \Gamma \vdash e : t \rrbracket$.

$\langle 2 \rangle 2$. LET: f be arbitrary; $\theta' \equiv \theta[fc \mapsto f]$.

Instantiate induction hypothesis with $k-1, \theta', \delta, \gamma, \sigma$,
to conclude $(\varsigma, \theta'(\gamma(\delta(e)))) \in \mathcal{C}_{k-1} \llbracket \theta'(t) \rrbracket$ (for all f , by 4.8).

$\langle 2 \rangle 3$. Instantiate *this* with j and \emptyset to conclude $\langle \theta(\sigma), \theta'(\gamma(\delta(e))) \rangle$
either takes j steps to **err** or a heap-and-expression $\langle \sigma', e' \rangle$ (for all f , by 4.8).

$\langle 2 \rangle 4$. CASE: j steps to **err**.

By OP_CONTEXT_ERR, whole expression reduces to **err** in $j < k-1$ steps (for $f = fc$).

$\langle 2 \rangle 5$. CASE: j steps to another heap-and-expression.

If it is not a value, then for $f = fc$, OP_CONTEXT runs j times and we are done.

$\langle 2 \rangle 6$. If it is, then $\exists i_e \leq j. (\varsigma', e') \in \mathcal{V}_{k-1-i_e} \llbracket \theta'(t) \rrbracket \subseteq \mathcal{V}_{k-1-j} \llbracket \dots \rrbracket$
by 4.3 and 4.5 (for all f , by 4.8).

$\langle 2 \rangle 7$. So, OP_CONTEXT runs i_e times, and then we have the following.

SUFFICES: By 4.4 i_e times, $(\varsigma', \mathbf{fun} fc \rightarrow e') \in \mathcal{V}_{k-i_e} \llbracket \theta(\forall fc. t) \rrbracket$ (for $f = fc$).

$\langle 2 \rangle 8$. ASSUME: Arbitrary f' .

SUFFICES: $(\varsigma', e'[fc/f']) \in \mathcal{V}_{k-1-i_e} \llbracket \theta(t)[fc/f'] \rrbracket$ (for $f = fc$).

$\langle 2 \rangle 9$. This is true by instantiating $\langle 2 \rangle 6$ with $f = f'$.

$\langle 1 \rangle 11$. CASE: TY_SPC.

$\langle 2 \rangle 1$. By induction, $\forall k. {}_k \llbracket \Theta; \Delta; \Gamma \vdash e : \forall fc. t \rrbracket$.

$\langle 2 \rangle 2$. Instantiate with $k, \theta, \delta, \gamma, \sigma$ to conclude $(\varsigma, \theta(\delta(\gamma(e)))) \in \mathcal{C}_k \llbracket \theta(\forall fc. t) \rrbracket$.

$\langle 2 \rangle 3$. Instantiate *this* with j and \emptyset and to conclude $\langle \theta(\sigma), \theta(\delta(\gamma(e))) \rangle$
either takes j steps to **err** or a heap-and-expression $\langle \sigma_f, e_f \rangle$.

$\langle 2 \rangle 4$. CASE: j steps to **err**.

By OP_CONTEXT_ERR, the whole expression reduces to **err** in $j < k$ steps.

$\langle 2 \rangle 5$. CASE: j steps to another heap-and-expression.

If it is not a value, then OP_CONTEXT runs j times and we are done.

$\langle 2 \rangle 6$. If it is, then $\exists i_e \leq j. (\varsigma_f, e_f) \in \mathcal{V}_{k-i_e} \llbracket \theta(\forall fc. t) \rrbracket \subseteq \mathcal{V}_{k-j} \llbracket \dots \rrbracket$ by 4.3 and 4.5.
So $e_f \equiv \mathbf{fun} fc \rightarrow v$ for some v .

$\langle 2 \rangle 7$. So, OP_CONTEXT runs i_e times, and then we have the following.

SUFFICES: By 4.4 i_e times, $(\varsigma_f, (\mathbf{fun} fc \rightarrow v)[f]) \in \mathcal{C}_{k-i_e} \llbracket \theta(t[fc/f]) \rrbracket$.

SUFFICES: By 4.4 once more, $(\varsigma_f, v[fc/f]) \in \mathcal{C}_{k-i_e-1} \llbracket \theta(t[fc/f]) \rrbracket$.

$\langle 2 \rangle 8$. This is true by instantiating $\langle 2 \rangle 6$ with f and 4.2.

$\langle 1 \rangle 12$. CASE: TY_FIX.

SUFFICES: $(\emptyset, \theta(\delta(\mathbf{fix}(g, x : t, e : t'))))) \in \mathcal{V}_k \llbracket \theta(t \multimap t') \rrbracket$, by 4.2 ($\sigma = \{\}$, $\gamma = []$).

ASSUME: Arbitrary $j \leq k$, $(\varsigma_v, v) \in \mathcal{V}_j \llbracket \theta(t) \rrbracket$ ($\varsigma = \emptyset$, so $\varsigma \star \varsigma_v$ is defined).

- LET: $\tilde{e} \equiv \theta(\delta(e))$.
 SUFFICES: $(\varsigma_v, \mathbf{fix}(g, x : t, \tilde{e} : t') \ v) \in \mathcal{C}_j[\![\theta(t')]\!]$.
 SUFFICES: $(\varsigma_v, \tilde{e} [x/v] [g/\mathbf{fix}(g, x : t, \tilde{e} : t')]) \in \mathcal{C}_{j-1}[\![\theta(t')]\!]$ by 4.4.
- $\langle 2 \rangle 1$. By induction, $\forall k. {}_k[\![\Theta; \Delta, g : t \multimap t'; x : t \vdash e : t']]\!]$.
- $\langle 2 \rangle 2$. Instantiate this with $j - 1, \delta[g \mapsto \mathbf{fix}(g, x : t, \tilde{e} : t')], \gamma = [x \mapsto v], \sigma_v$.
- $\langle 2 \rangle 3$. We have $(\emptyset, \mathbf{fix}(g, x : t, \tilde{e} : t')) \in \mathcal{V}_{j-1}[\![\theta(t \multimap t')]\!]$.
- $\langle 3 \rangle 1$. Again by induction (over k), $(\emptyset, \mathbf{fix}(g, x : t, \tilde{e} : t')) \in \mathcal{C}_{j-1}[\![\theta(t \multimap t')]\!]$.
- $\langle 3 \rangle 2$. Instantiate *this* with $j = 0$ and \emptyset and we are done.
- $\langle 2 \rangle 4$. We have $(\varsigma_v, v) \in \mathcal{V}_{j-1}[\![\theta(t)]\!]$ by assumption and 4.5.
- $\langle 2 \rangle 5$. So we conclude $(\varsigma_v, \theta(\delta'(\gamma(e)))) \in \mathcal{C}_{j-1}[\![\theta(t')]\!]$ as required.
- $\langle 1 \rangle 13$. CASE: TY_VAR_LIN.
 PROVE: $(\varsigma, \theta(\delta(\gamma(x)))) \in \mathcal{C}_k[\![\theta(t)]\!]$.
- $\langle 2 \rangle 1$. $\Gamma = \{x : t\}$ by assumption of TY_VAR_LIN.
- $\langle 2 \rangle 2$. SUFFICES: $(\varsigma, \gamma(x)) \in \mathcal{C}_k[\![\theta(t)]\!]$ by 3 (θ and δ irrelevant).
- $\langle 2 \rangle 3$. By 2c, there exist $(\varsigma_x, v_x) \in \mathcal{V}_k[\![\theta(t)]\!]$, such that $\varsigma = \varsigma_x$ and $\gamma = [x \mapsto v_x]$.
- $\langle 2 \rangle 4$. Hence, $(\varsigma_x, v_x) \in \mathcal{C}_k[\![\theta(t)]\!]$, by 4.2.
- $\langle 1 \rangle 14$. CASE: TY_VAR.
 PROVE: $(\varsigma, \theta(\delta(\gamma(x)))) \in \mathcal{C}_k[\![\theta(t)]\!]$.
- $\langle 2 \rangle 1$. $x : t \in \Delta$ and $\Gamma = \emptyset$ by assumption of TY_VAR.
- $\langle 2 \rangle 2$. SUFFICES: $(\emptyset, \delta(x)) \in \mathcal{C}_k[\![\theta(t)]\!]$ by 3.
- $\langle 2 \rangle 3$. By 2b, there exists v_x such that $(\emptyset, v_x) \in \mathcal{V}_k[\![\theta(t)]\!]$ (θ irrelevant and γ empty).
- $\langle 2 \rangle 4$. Hence, $(\emptyset, v_x) \in \mathcal{C}_k[\![\theta(t)]\!]$, by 4.2.
- $\langle 1 \rangle 15$. CASE: TY_UNIT_INTRO.
 True by 4.2 and definition of $\mathcal{V}_k[\![\mathbf{unit}]\!]$.
- $\langle 1 \rangle 16$. CASE: TY_BOOL_TRUE, TY_BOOL_FALSE, TY_INT_INTRO, TY_ELT_INTRO.
 Similar to TY_UNIT_INTRO.

6 Additional Details

6.1 Well-formed types

$\boxed{\Theta \vdash f \text{ Perm}}$ Well-formed fractional permissions

$\frac{fc \in \Theta}{\Theta \vdash fc \text{ Perm}}$ WF_PERM_VAR

$\frac{}{\Theta \vdash 1 \text{ Perm}}$ WF_PERM_ZERO

$\frac{\Theta \vdash f \text{ Perm}}{\Theta \vdash \frac{1}{2}f \text{ Perm}}$ WF_PERM_SUCC

$\boxed{\Theta \vdash t \text{ Type}}$ Well-formed types

$\frac{}{\Theta \vdash \mathbf{unit} \text{ Type}}$ WF_TYPE_UNIT

$\frac{}{\Theta \vdash \mathbf{bool} \text{ Type}}$ WF_TYPE_BOOL

$\frac{}{\Theta \vdash \mathbf{int} \text{ Type}}$ WF_TYPE_INT

$\frac{}{\Theta \vdash \mathbf{elt} \text{ Type}}$ WF_TYPE_ELT

$\frac{\Theta \vdash f \text{ Perm}}{\Theta \vdash f \mathbf{arr} \text{ Type}}$ WF_TYPE_ARRAY

$\frac{\Theta \vdash t \text{ Type}}{\Theta \vdash !t \text{ Type}}$ WF_TYPE_BANG

$\frac{\Theta, fc \vdash t \text{ Type}}{\Theta \vdash \forall fc. t \text{ Type}}$ WF_TYPE_GEN

$\frac{\Theta \vdash t \text{ Type} \quad \Theta \vdash t' \text{ Type}}{\Theta \vdash t \otimes t' \text{ Type}}$ WF_TYPE_PAIR

$\frac{\Theta \vdash t \text{ Type} \quad \Theta \vdash t' \text{ Type}}{\Theta \vdash t \multimap t' \text{ Type}}$ WF_TYPE_LOLLY

6.2 Grammar Definition

| | | |
|-----|-----------------------|-----------------------|
| m | $::=$ | matrix expressions |
| | $ \quad M$ | matrix variables |
| | $ \quad m + m'$ | matrix addition |
| | $ \quad m \, m'$ | matrix multiplication |
| | $ \quad (m) \quad S$ | |

| | | | |
|-----|-------|------------------|---|
| f | $::=$ | | fractional permission |
| | | fc | variable |
| | | 1 | whole permission |
| | | $\frac{1}{2}f$ | |
| t | $::=$ | | linear type |
| | | unit | unit |
| | | bool | boolean (true/false) |
| | | int | 63-bit integers |
| | | elt | array element |
| | | f arr | arrays |
| | | f mat | matrices |
| | | $!t$ | multiple-use type |
| | | $\forall fc.t$ | bind fc in t frac. perm. generalisation |
| | | $t \otimes t'$ | pair |
| | | $t \multimap t'$ | linear function |
| | | (t) | S parentheses |
| p | $::=$ | | primitive |
| | | not | boolean negation |
| | | $(+)$ | integer addition |
| | | $(-)$ | integer subtraction |
| | | $(*)$ | integer multiplication |
| | | $(/)$ | integer division |
| | | $(=)$ | integer equality |
| | | $(<)$ | integer less-than |
| | | $(+.)$ | element addition |
| | | $(-.)$ | element subtraction |
| | | $(*.)$ | element multiplication |
| | | $(/.)$ | element division |
| | | $(=.)$ | element equality |
| | | $(<.)$ | element less-than |
| | | set | array index assignment |
| | | get | array indexing |
| | | share | share array |
| | | unshare | unshare array |
| | | free | free array |
| | | array | Owl: make array |
| | | copy | Owl: copy array |
| | | sin | Owl: map sine over array |
| | | hypot | Owl: $x_i := \sqrt{x_i^2 + y_i^2}$ |
| | | asum | BLAS: $\sum_i x_i $ |
| | | axpy | BLAS: $x := \alpha x + y$ |
| | | dot | BLAS: $x \cdot y$ |
| | | rotmg | BLAS: see its docs |
| | | scal | BLAS: $x := \alpha x$ |
| | | amax | BLAS: $\operatorname{argmax} i : x_i$ |
| | | setM | matrix index assignment |

| | | | | |
|-----|-----|--|------------------------|---|
| | | getM | | matrix indexing |
| | | shareM | | share matrix |
| | | unshareM | | unshare matrix |
| | | freeM | | free matrix |
| | | matrix | | Owl: make matrix |
| | | copyM | | Owl: copy matrix |
| | | copyM_to | | Owl: copy matrix onto another |
| | | sizeM | | dimension of matrix |
| | | trnsp | | transpose matrix |
| | | gemm | | BLAS: $C := \alpha A^{T?} B^{T?} + \beta C$ |
| | | symm | | BLAS: $C := \alpha AB + \beta C$ |
| | | posv | | BLAS: Cholesky decomp. and solve |
| | | potrs | | BLAS: solve with given Cholesky |
| | | syrk | | BLAS: $C := \alpha A^{T?} A^{T?} + \beta C$ |
| v | ::= | | | values |
| | | p | | primitives |
| | | x | | variable |
| | | $()$ | | unit introduction |
| | | true | | true |
| | | false | | false |
| | | k | | integer |
| | | l | | heap location |
| | | el | | array element |
| | | Many v | | !-introduction |
| | | fun $fc \rightarrow v$ | | frac. perm. abstraction |
| | | (v, v') | | pair introduction |
| | | fun $x : t \rightarrow e$ | bind x in e | abstraction |
| | | fix $(g, x : t, e : t')$ | bind $g \cup x$ in e | fixpoint |
| | | (v) | S | parentheses |
| e | ::= | | | expression |
| | | p | | primitives |
| | | x | | variable |
| | | let $x = e$ in e' | bind x in e' | let binding |
| | | $()$ | | unit introduction |
| | | let $() = e$ in e' | | unit elimination |
| | | true | | true |
| | | false | | false |
| | | if e then e_1 else e_2 | | if |
| | | k | | integer |
| | | l | | heap location |
| | | el | | array element |
| | | Many e | | !-introduction |
| | | let Many $x = e$ in e' | | !-elimination |
| | | fun $fc \rightarrow e$ | | frac. perm. abstraction |
| | | $e[f]$ | | frac. perm. specialisation |
| | | (e, e') | | pair introduction |

| | | | | |
|----------|-------|---|---------------------------------------|-----------------------------------|
| | | let $(a, b) = e$ in e' | bind $a \cup b$ in e' | pair elimination |
| | | fun $x : t \rightarrow e$ | bind x in e | abstraction |
| | | $e e'$ | | application |
| | | fix $(g, x : t, e : t')$ | bind $g \cup x$ in e | fixpoint |
| | | (e) | S | parentheses |
| C | $::=$ | | | evaluation contexts |
| | | let $x = [-]$ in e | bind x in e | let binding |
| | | let $() = [-]$ in e | | unit elimination |
| | | if $[-]$ then e_1 else e_2 | | if |
| | | Many $[-]$ | | !-introduction |
| | | let Many $x = [-]$ in e | | !-elimination |
| | | fun $fc \rightarrow [-]$ | | frac. perm. abstraction |
| | | $[-][f]$ | | frac. perm. specialisation |
| | | $([-], e)$ | | pair introduction |
| | | $(v, [-])$ | | pair introduction |
| | | let $(a, b) = [-]$ in e | bind $a \cup b$ in e | pair elimination |
| | | $[-]e$ | | application |
| | | $v[-]$ | | application |
| Θ | $::=$ | | | fractional permission environment |
| | | . | | |
| | | Θ, fc | | |
| Γ | $::=$ | | | linear types environment |
| | | . | | |
| | | $\Gamma, x : t$ | | |
| | | Γ, Γ' | | |
| Δ | $::=$ | | | intuitionistic types environment |
| | | . | | |
| | | $\Delta, x : t$ | | |
| σ | $::=$ | | | heap (multiset of triples) |
| | | $\{\}$ | | empty heap |
| | | $\sigma + \{l \mapsto_f m_{k_1, k_2}\}$ | | location l points to matrix m |
| $Config$ | $::=$ | | | result of small step |
| | | $\langle \sigma, e \rangle$ | | heap and expression |
| | | err | | error |